SYSTEM STUDY FOR AN INDUCTIVE GENERATOR

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Abstract

A system study has been initiated to aide in the design of the inductive pulsed power generator prototype, CHECMATE.[1] Because of the highly interactive nature of the opening switches with the other elements of the pulsed power system, this study requires that realistic physics models of the switch and load elements be coupled to the circuit in a self-consistent manner. This has been accomplished using a transmission line code in conjunction with an empirical model for fuse resistivity and various physics models for a plasma flow switch and a load. System optimization will be discussed. This system analysis technique can be applied to higher energy inductive generators.

Introduction

Inductive energy storage techniques have advantages over conventional capacitive techniques for high energy pulsed power systems in that energy can be stored more compactly and at low voltage.[2] The opening switches in such a system are the critical elements. The DNA CHECMATE[1] facility being built at Maxwell Laboratories is designed to take advantage of inductive storage techniques. High energy density capacitors (~ 50 kJ/can) will be used to slowly (~ 20µs) charge a storage inductor and then a succession of two opening switch stages will compress the pulse to ~ 100 ns. It is presently envisioned that six parallel storage inductors will be energized (~ 20 µs) through individual fuses.[3] When the fuses open (~ 1 µs), the energy will flow into a common disc feed linked to a second vacuum opening switch, which is expected to open in ~ 100 ns into either a brehmsstrahlung diode source (BDS) load or a plasma radiation source (PRS) load. For this study the plasma flow switch (PFS)[4] will be used as the second vacuum switch.

Because of the highly interactive nature of the opening switches with the other elements of the pulsed power system, a system study is required to optimize the CHECMATE system parameters. A transmission line code[5] is used to analyze the system and realistic physic models for the switches are included.

The objectives of this study are: (1) to develop the understanding for optimizing the system in terms of energy and/or current available to drive a load, (2) to identify areas requiring strong research efforts in order to ensure this optimization and (3) to predict system performance using the present models. In the next section the system is described in more detail. The sections which follow include a basic system study intended to give an intuitive feel for the problem and a detailed system study where more realistic modeling is done. A summary of the conclusions from this work are contained in the last section.

System Description

An equivalent circuit diagram for CHECMATE is shown in Fig. 1. The accompanying plot illustrates the two stages of compression. Here I_F is the charging current through the fuse, I_0 is the output current through the PFS and I_ℓ is the load current.
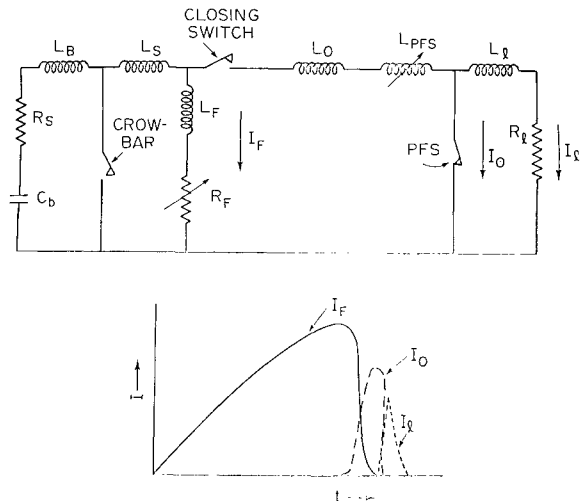

Fig. 1   Equivalent circuit and typical current waveforms.

The capacitor bank (6 modules) is represented by a capacitance, C_b = 6,158 µF, an inductance, L_B = 6 nH, and a resistance, R_S = 0.533 m Ω.   Included in R_S is the internal bank resistance, safety resistors to reduce damage if a fault mode occurs and the skin resistance of the storage inductance. The capacitor is initially charged to 44 kV (6 MJ stored). The crowbar switch is closed when the PFS opens and is used to prevent voltage reversal on the bank.

The fuse package is represented by a fuse inductance, L_F, and a time varying fuse resistance, R_F. The present fuse model is based on experimental data for #27 copper wire.[3] The resistivity, ρ, of the fuse is specified as a function of energy density, ε, which is obtained by integration of the instantaneous joule heating rate resulting from current driven through the fuse. The fuse resistance $R_F = \rho(\varepsilon)H/S$ where H is the fuse height and S is the cross-sectional area. The fuse height is chosen to be 0.5 m in order to maintain the assumed holdoff of ~ 20 kV/cm when the peak load voltage of ~ MV is reached. The fuse begins to open at $\varepsilon = \varepsilon_1 = 3 \times 10^{10}$ J/m^3 where the slope of $\rho(\varepsilon)$ has a sharp increase and the fuse begins to become resistive. The closing switch following the fuse is closed when the fuse begins to open. When $\varepsilon = \varepsilon_2 = 4.5 \times 10^{10}$ J/m^3 the fuse is open. For the purposes of this system study the fuse is designed so that ε_2 is reached when the PFS is about to open. At this point R_F is set equal to 2 Ω which is the value of the grading resistor in parallel with the fuse wires. This basically assumes that the fuse remains open and does not restrike.

The output inductance consists of a constant inductance, L_0, and an increasing inductance, L_{PFS}, associated with the motion of the PFS. The PFS is a moving plasma opening switch.[4] The plasma is accelerated downstream by the JXB force and opens when the plasma crosses a gap. The trailing low density plasma must be controlled in such a way that the current is commutated. For this study the mass

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14. ABSTRACT
A system study has been initiated to aide in the design of the inductive pulsed power generator prototype, CHECMA TE. 1 Because of the highly interactive nature of the opening switches with the other elements of the pulsed power system, this study requires that realistic physics models of the switch and load elements be coupled to the circuit in a self-consistent manner. This has been accomplished using a transmission line code in conjunction with an empirical model for fuse resistivity and various physics models for a plasma flow switch and a load. System optimization will be discussed. This system analysis technique can be applied to higher energy inductive generators.

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of the PFS was assumed to be 15 mg with a 5 cm travel in a 20-cm OD, 15-cm ID cylindrical vacuum inductor (L_{PFS} = 2.9 nH). The opening process for the PFS is difficult to model and is discussed elsewhere.[6] Here it is assumed that the PFS opens into a constant resistance load, R_ℓ, with a load current risetime of ~ 100 ns. The load inductance, L_ℓ, is assumed to be 2 nH. Diode and imploding gas puff load models exist and will be used in the future when load coupling to the final switching stage is studied in more detail.

Basic Study

The purpose of this basic study is to develop an intuitive picture for the operation of the system and how to optimize the output current and energy available to drive the load. First the simple circuit shown in Fig. 2a is run until the fuse energy density reaches ε_1. This specifies I_F at the time the fuse begins to open in terms of the free parameters S and L_{TOT} = L_S + L_F. Here L_S includes the 6 nH bank inductance, L_B. The fuse is now assumed to open on a very short timescale so that the sudden approximation can be applied to the circuit in Fig. 2b. Under this approximation energy is conserved,

$$E_A = 1/2 \ (L_0 + L_S) I_0^2 = 1/2 \ L_{TOT}^2 I_F - (\varepsilon_2 - \varepsilon_1) SH, \qquad (1)$$

and the flux stored in L_S is conserved,

$$L_S I_F = (L_0 + L_S) I_0. \qquad (2)$$

This introduces another free parameter, L_0, which is assumed to be constant (i.e., before any PFS motion). Equations (1) and (2) can then be solved for the output current $I_0(L_{TOT}, S, L_0)$ and the fuse inductance $L_F(L_{TOT}, S, L_0)$. In addition, the available energy, $E_A(L_{TOT}, S, L_0)$, defined in Eq. (2), can also be calculated from I_0.
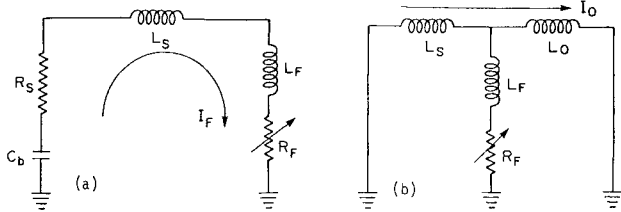
Fig. 2   Schematic of (a) charging circuit and (b) output circuit.

The results are plotted for a typical L_0 = 10 nH in Figs. 3, 4 and 5. The output current shown in Fig. 3 has a peak of 9.6 MA in this case at S = 1.1 cm^2 and L_{TOT} = 22.5 nH. For larger L_{TOT} the current that can be driven by the capacitor bank through the fuse circuit is smaller and thus I_0 is smaller. For smaller L_{TOT} the output inductance becomes comparable with L_S and the conservation of flux dictates a smaller I_0. For smaller S the fuse opens earlier before the current rises to its full value resulting in lower I_0. And for larger S the fuse requires a larger fraction of the energy to reach the required energy density for opening, thus limiting I_0.

The available energy, E_A, shown in Fig. 4 has a maximum value of ~ 2.3 MJ at S ~ 0.95 cm^2 and at L_{TOT} ~ 60 nH. Arguments similar to those presented for I_0 can explain the behavior of E_A (L_{TOT},S). The
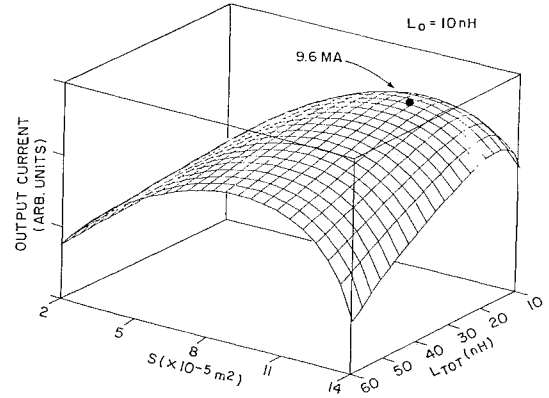
Fig. 3   Output current as a function of S and L_{TOT} for L_0 = 10 nH.
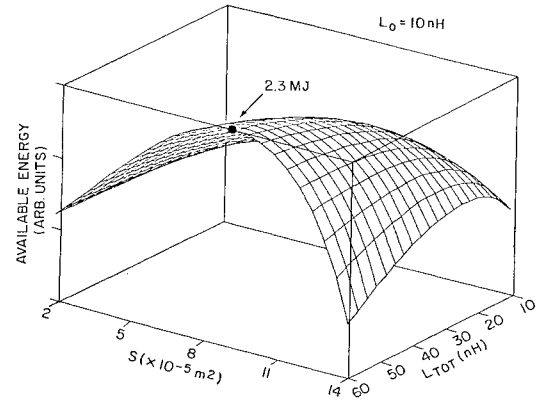
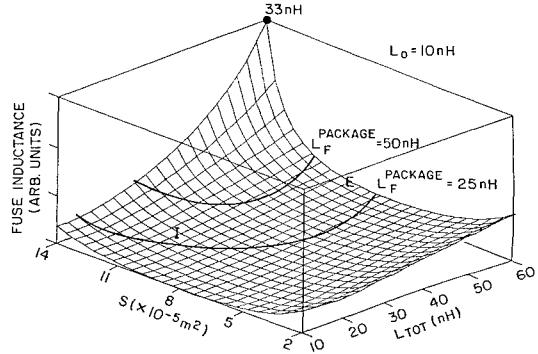Fig. 4   Available energy as a function of S and L_{TOT} for L_0 = 10 nH.

Fig. 5   Fuse inductance as a function of S and L_{TOT} for L_0 = 10 nH.

peak in E_A occurring at a larger L_{TOT} than the peak in I_0 results because $L_0 + L_S = L_0 + L_{TOT} - L_F(L_{TOT}, S)$ increases more rapidly than $I_0^2 (L_{TOT}, S)$ is decreasing until L_{TOT} reaches ~ 60 nH.

The fuse inductance is plotted as a function of L_{TOT} and S in Fig. 5. The points marked by "I" and "E" indicate where the peaks of Figs. 3 and 4 occur. Note that this surface is being viewed from behind compared with the other two surfaces in Figs. 3 and 4. Curves are also drawn for $L_F^{package}$= 25 nH and 50 nH where $L_F = L_F^{package}/6$. Physical constraints on designing the fuse package for each of the six modules limit how small L_F can be made.

These results indicate that $L_F^{package} \sim 25$ nH is required to reach the peaks in I_O and E_A. A 50 nH single fuse package is easily attainable, while a 25 nH is optimistic. For the detailed study that follows a realistic L_F of 6 nH will be assumed (i.e., $L_F^{package} = 36$ nH).

For a BDS load the power weighted voltage pulse (the characteristic shape of the radiation pulse) should have a full width half maximum of ≤ 100 ns, and the peak voltage should be ≤ 1.5 MV. Combining these constraints yields the condition

$$I_O < 0.65/(L_S + L_O), \qquad (3)$$

where now L_S is the storage inductance only and does not include the bank inductance because crowbarring will occur before current to diverted to the load. This condition is easily satisfied for the CHECMATE system when operating in the region near the peaks in I_O and E_A.

In summary the basic study provides an intuitive understanding of the system operation and shows that the system can be designed to optimize either I_O or E_A by operating at different points in L_{TOT} and S. For a BDS load, operation near peak E_A is probably desirable[9], while for a PRS load, operation near peak I_O is probably desirable. As expected doing the same analysis for various values of L_O show that L_O should be made as small as physically possible in order to maximize I_O and E_A. Increasing H reduces I_O and E_A because more energy is required to open the fuse. Decreasing H makes the fuse holdoff requirements more severe and does not gain in I_O and E_A because their peaks are less attainable as a result of more severe constraints on $L_F^{package}$ than those shown in Fig. 5. Thus $H \sim 0.5$ m is about optimum. Reducing $L_F^{package}$ to ~ 25 nH, allows operation at the peaks in I_O and E_A. Finally, the conditions on the BDS output [Eq. (3)] do not present any constraints on the CHECMATE system design although designing the low impedance (~ 0.3 Ω) diode itself may be difficult.

Detailed Study

In the detailed study, first the run down of the PFS and the full fuse model are included in a transmission line code in order to study their effect on the system operation. Then the PFS opening is modeled and energy delivery to a load is investigated with the intent of doing an energy inventory and studying switching efficiencies.

The PFS is assumed to have a mass of 15 mg and travel a distance of 5 cm before reaching an opening gap. For the assumed geometry $L_{PFS} = 2.8$ nH ($r_i = 7.5$ cm, $r_o = 10$ cm). Typical run down times of ~ 2 μs and final velocities of ~ 10 cm/μs were observed using a simple slug model with magnetic pressure. By fixing S = 1.3 cm^2 and varying L_{TOT} or fixing $L_{TOT} = 32$ nH and varying S, the results of this more complete analysis can be compared with the basic study results presented in Figs. 3, 4 and 5. In Fig. 6 the solid curves are from the basic study and the curves marked with "+" signs are from the detailed study. Note that graphs in Fig. 6 are plotted in terms of $L_S = L_{TOT} - L_F$. Although I_O and E_A are reduced, the nature of the curves remains the same. The added inductance of the PFS, the energy extracted to accelerate the PFS mass and the time dependent fuse dynamics all play a role in reducing
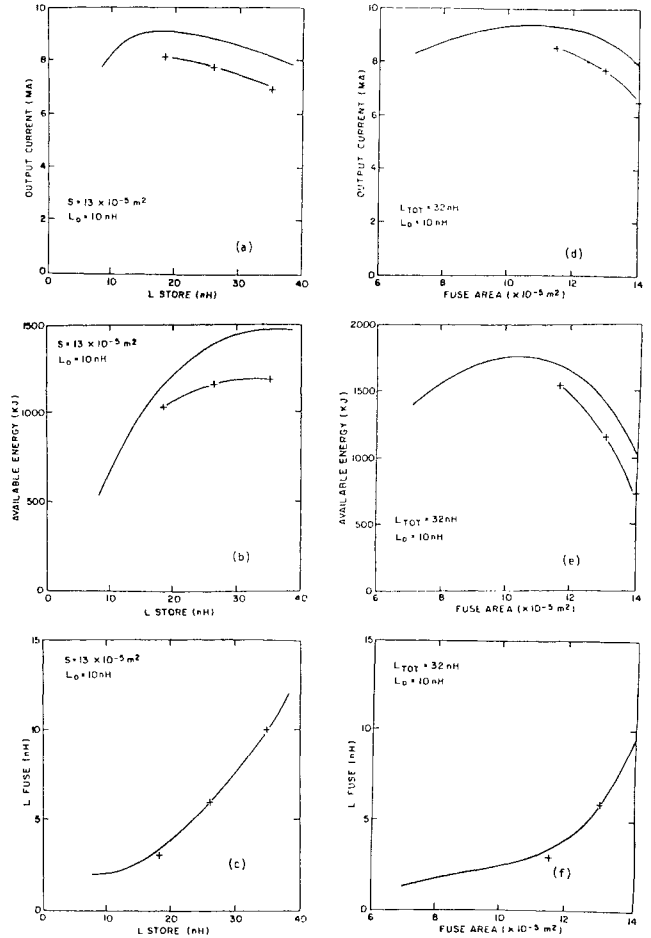

Fig. 6 Comparison of detailed study (marked by "+") with basic study (solid curve) where S is fixed at 1.3 cm^2 in (a), (b) and (c) and L_{TOT} is fixed at 32 nH in (c), (d) and (e).

I_O and E_A. The fuse inductance remains nearly the same.

The PFS opening is modeled here by a time varying shunt resistance in parallel with the load which allows the load current to rise in ~ 100 ns. A more realistic model is still in the developmental stages.[6] The BDS load is modeled by an inductance of 2 nH and a constant 0.3 Ω resistance. This value of resistance was chosen so that the peak load voltage would be 1.5 MV. Crowbarring is assumed to occur at the end of the PFS run down, prior to opening. It is also assumed at this time that the fuse is open so that R_F is set to the 2 Ω value of the grading resistor in parallel with the fuse. If the fuse does not open to a large resistance, or if the fuse restrikes, a large fraction of the energy which is available to drive the load will be deposited in the fuse.

For the load results discussed here $L_{TOT} = 32$ nH, S = 1.3 cm^2 and $L_F = 6$ nH. The results show peak load values of $V_\ell = 1.5$ MV, $I_\ell = 5$ MA and $P_\ell = 7.5$ TW. The full width half maximum of the voltage is ~ 135 ns and of the power weighted voltage is ~ 45 ns. A total of ~ 0.69 MJ was delivered to the load. The voltage across the fuse is shown in Fig. 7. The fuse itself generates ~ 0.25 MV when it opens and ~ 0.92 MV appears when the load voltage
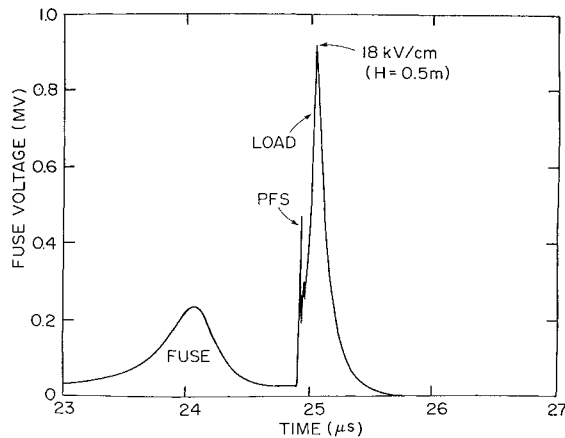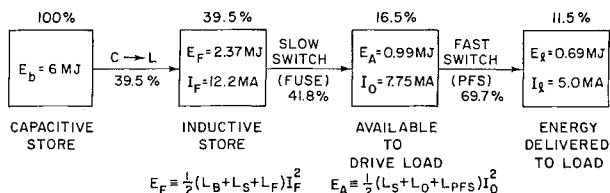
Fig. 7 Fuse voltage vs time.

peaks. This corresponds to 18 kV/cm, within the expected holdoff strength (20 - 30 kV/cm) for the fuse. This voltage is reduced from the full load voltage by inductive division. Results also show that before crowbarring the voltage across the insulator at the output of the bank peaks at ~ 30 kV well within the designed 100 kV holdoff.

Figure 8 shows a breakdown of the energy flow and an energy inventory. The percentages at the top of the boxes show what percentage of the original 6 MJ stored in the bank is still available at each stage. The percentages under each transfer stage show the efficiency of energy transfer for that stage. Note L_B is expressed explicitly here and is not included in L_S. An energy inventory is also given at the bottom. Improvement in the fuse performance would be most beneficial to improving the energy delivery to the load. The inductor to inductor transfer performed by the fuse must dissipate some energy but ideally this is only ~ 1/3 of the energy absorbed by the fuse. Reducing or removing the safety resistors in the bank is the other possible improvement which will have a large impact on the energy available to drive the load.

In summary the detailed study showed that the PFS motion and the time dependent fuse model reduce I_0 by ~ 10% amd E_A by ~ 20% for the cases studied but do not change the basic operation of the system. The energy delivered to the load, peak voltage and width of the power weighted voltage pulse are all within expectations for the models used. The fuse and insulator as presently envisioned should be capable of withstanding the voltage stress that will appear.

ENERGY INVENTORY:

R_F -	2.98 MJ (50%)	L_B -	0.14 MJ (2%)
R_S -	1.74 MJ (29%)	K_{PFS} -	0.08 MJ (1%)
R_ℓ -	0.69 MJ (12%)	R_{SKIN} -	0.02 MJ (0%)
R_{PFS} -	0.31 MJ (5%)		

Fig. 8 Energy transfer efficiency and inventory.

Conclusions

The major conclusion of this study is that the system as designed is close to optimum. Improvements in the fuse packaging to reduce its inductance to ~ 25 nH for a 0.5 m length fuse would maximize performance for the present model. However, replacement of the fuse with a more efficient opening switch or improvements in the amount of energy (= $\varepsilon_1 SH$) required to bring the fuse to the point of opening, could have a large impact on the system efficiency. Finally it must be stressed that, although realistic (non-ideal) assumptions were made throughout this study, the opening process of the final switch (the PFS in this study) into a BDS load is the least understood and warrants the strongest research effort.

Acknowledgements

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